Final Report on

Contract No. NAS 9-6177

DEVELOPMENT OF ELECTROFORMING TECHNIQUES FOR THE FABRICATION OF INJECTORS

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## Foreword

This report, which details the investigation of applying electroforming techniques to the fabrication of liquid propellant rocket motor injectors, was prepared by Camin Laboratories, Inc., Brooklyn, New York under NASA Contract NAS 9-6177. Mr. Samuel Fialkoff served as program manager. Dr. Sanford Hammer was project engineer, responsible for design, fabrication, and test of the prototype injectors. The electrochemical aspects of the program were conducted by Mr. Zdenek Cacka.

The program was administered under the direction of the Manned Spacecraft Center, General Research Procurement Branch. The Technical Monitor was Mr. Norman H. Chaffee and the Technical Representative was Mr. Sam V. Glorioso.

The work reported herein was performed during the period 21 June 1966 to 21 April 1967.

#### I. SUMMARY

A program was conducted to demonstrate the capability of utilizing electroforming techniques in the design and fabrication of liquid propellant rocket motor injectors. A laboratory scale program was conducted to define and develop the electroforming process variables and techniques required for the successful fabrication of electrodeposited injectors. Upon completion of this phase of the project multiple doublet and multiple triplet injectors were designed and subsequently approved by the NASA Technical Monitor. Four injectors of each configuration were fabricated and subjected to hydraulic testing for the purpose of defining hardware reproductibility.

The results of this program indicate that electroforming techniques are capable of producing injectors having complex internal propellant flow passages, incorporating fewer components and subassemblies devoid of press fits, welds, and brazes with demonstrated reproducible hydraulic characteristics.

### II. INTRODUCTION

The practical problems involved in the manufacture of injector systems for liquid propellant rocket motors can impose severe restrictions on the design and increase the cost of completed propulsion systems. From a design point of view, orifice layout on the injector face is often compromised by the ability or inability to internally manifold the fuel and oxidizer. Injectors fabricated by conventional techniques consist of several subassemblies, welded, bolted or press fitted together, in order to achieve an acceptable manifolding arrangement and resultant orifice distribution. The need to incorporate several components into a single injector leads to increased costs and decreased reliability.

During fabrication of a quantity of injectors it is possible to employ a single tooling utilizing gang drilling techniques. However, each hole in every injector still represents a potential pitfall due to the frequency of drill breakage and the inability to successfully dislodge that portion of the

drill bit that remains in the injector plate.

Misalignment of the tooling on any single hole
results in an injector with different spray characteristics than its counterparts.

Many of the orifices are drilled from the injector side into a blind manifold. This eliminates the possibility of inspecting and deburring or chamfering the entrance to the orifice. This too can result in injectors with dissimilar hydraulic characteristics.

The successful efforts of Camin Laboratories in the design and fabrication of electroformed regeneratively cooled liquid propellant rocket motor chambers and nozzles (ref. 1, 2, 3) suggested the development of electroforming techniques for injector fabrication. Successful application of electroforming would result in an ability to manufacture many injectors from a single "master," insuring reproducibility in flow passages and hydraulic characteristics. An added advantage would be the elimination of multi-pieced construction and attendant joints. Perhaps the greatest advantage would be the freedom to design orifice patterns that are not restricted by internal manifolding which in turn is

restricted by machining limitations.

The electroforming process is basically a method of fabricating intricate metal parts entirely by electrodeposition. A male form or mandrel is inserted into an electrolytic solution, a metallic deposit accumulated, and the male mandrel is extracted from the deposited metal after the required thickness or form has been attained. The total thickness can be accumulated in stages so that intermediate machining and placement of filler materials for the creation of hollow areas or manifolding can be accomplished. This of course requires that proper processing be employed so that adhesion is obtained between intermediate metallic layers. Variations of the basic techniques can thus result in a one piece injector devoid of welds, joints, etc.

A method to electroform injectors was proposed that involved the creation of a single master plate by ordinary machining methods. This plate is actually a transfer of the final injector face. Holes in the master plate, representing the injector orifice layout, would then be fitted with pins or precise I.D.

tubing. Electroforming techniques would then be utilized to generate a multiplicity of "slaves" or injectors from the single master plate. The orifices in the electroform are created by either the I.D. of the tubing or the holes formed when the disposable pins are removed. Internal feed passages and manifolding are created during the process by interrupting the deposition cycle and incorporating disposable filler materials. Inspection and deburring of the entrances to the orifices can be accomplished at these times. The final product would be a series of injectors reproduced from a single machined master, devoid of any welds or brazes.

A program was undertaken with an objective to demonstrate the capability of electroforming techniques to increase reliability, reproducibility, and design flexibility in the design and manufacture of injector systems. The program is divided into three phases. The first phase consists of an analytical and laboratory scale program to define and develop the electroforming process variables required to successfully electroform injectors.

Phase 2 of the program consists of the design and fabrication of 8 on 8 multiple doublet and 12 on 6 multiple triplet internally manifolded injectors. Four units of each configuration are to be manufactured and subjected to hydraulic testing for the purpose of defining hardware reproducibility.

Phase 3 of the program consists of an analysis of the Apollo Service Module (S/M) Reaction Control System (RCS) rocket engine for the purpose of recommending methods of incorporating electroforming techniques in the design and fabrication of the S/M RCS engine injector.

## III. DEVELOPMENT OF ELECTROFORMING TECHNIQUES

The laboratory scale investigation of the definition and development of the electroforming techniques required to successfully electroform injectors can be divided into three categories;

- A. Electroforming Bath
- B. Master Plate Material
- C. Creation of Orifices.

## A. The Electroforming Bath

The initial injector fabrication feasibility studies have been conducted using nickel as the material to be electroformed. The composition of the electrolyte is:

	oz/gal
Nickel Sulfamate, Ni(NH <sub>2</sub> SO <sub>3</sub> ) <sub>2</sub>	45
Nickel metal content	10.2
Nickel Chloride NiCl <sub>2</sub> °6H <sub>2</sub> 0	.8 to 2.0
Boric Acid, H <sub>3</sub> BO <sub>3</sub>	4.0

The range of operating conditions for this bath formulation is:

Temperature Range 100-140°F

pH Range 3.5-5.0 electrometric

Density (degrees Baume') 29-31

Tank Voltage 6-9 volts

The above bath has been selected primarily because of the low internal stresses in the deposited metal. All laboratory and prototype electroforming has been performed in a Module-X Jet Plater (trademark of the Sel-Rex Corporation, Nutley, New Jersey). This unit contains an integral electrical control console, with rectified power supply, controls and monitoring meters. Internal components include systems for continuous filtration, solution agitation and bath temperature controls.

Tensile specimens were prepared and submitted for test at room temperature, 500°F and 1000°F. A copy of the test report and a drawing of the specimen is contained in Appendix A. The results are in accordance with data obtained previously for metallic deposits from the above bath formulation.

## B. Master Plate Material

The master plate material must possess certain characteristics in order to generate a multiplicity

of injectors. It must not be attacked by the plating solution; it must accept a nickel deposit; it must be machineable; and it must be able to withstand repeated deposits and stripping of the slaves while retaining its dimensions and finish.

An evaluation of stainless steel (304), aluminum and cold rolled steel was conducted. The steels were hard chrome plated and the aluminum was anodized in an attempt to protect them from the corrosive action of the bath. The specimens were repeatedly cycled through pre-plating processing, electroforming and stripping operations. The aluminum showed a tendency to etch and scratch while the steels appeared satisfactory in that they are able to withstand repeated plating and stripping operations without loss of finish or dimensional accuracy. The chrome plated cold rolled steel has the added advantage of being more easily machined.

The need to hard chrome plate (to a thickness of .0005") either the stainless or cold rolled steel in order to afford protection from the bath presents a problem in terms of creating accurate holes to position tubes or rods for creation of

orifices. If the master plate is chrome plated prior to drilling the pin positioning holes, the drilling process is difficult due to the hardness of the chrome. On the other hand if the master plate is drilled prior to chrome plating, it is difficult to obtain an accurate fit of the pin in the chrome plated hole.

As a result of these findings and the need to remove the orifice creating pin material from the electroform (see section C) by etching in hot sodium hydroxide or hydrofluoric acid, attention focused on the detailed evaluation of pure nickel as a master plate material. If the pin material is to be removed from a nickel electroform by chemical attack without disturbing the size or finish of the electroform, then a nickel master plate should also be impervious to the chemical solution.

The use of hot sodium hydroxide as a disposal agent for aluminum mandrels in nickel electroforms is an historical technique. Radar waveguides, plastic mold cavities and rocket engine components have been fabricated at Camin Laboratories

using aluminum mandrels, with subsequent mandrel removal by immersion in hot sodium hydroxide. The nickel electroform is not affected by the immersion in hot sodium hydroxide.

Tests were conducted to determine the resistance of nickel to immersion in hydrofluoric acid. Samples of electrolytic nickel were placed in a 25% by weight solution of hydrofluoric acid for periods up to thirty minutes. No variations of size or surface finish were noticed. These tests were confirmed by the International Nickel Company.

Samples of the pin material (0.032" diameter) were press-fitted into 0.032" diameter holes to a depth of 1/4" in nickel plates. The pin was removed by dissolving it in hydrofluoric acid. The nickel plate was subjected to visual and dimensional inspection. The results were completely satisfactory. In addition, new specimens of pins were fitted into the original hole with as good a fit as originally obtained. This test was repeated several times, indicating that the nickel master can be reused after immersion in hydrofluoric acid.

In order that the nickel deposit does not adhere to the nickel master plate steps must be taken to passivate the surface of the mandrel prior to deposition. This can be accomplished by immersing the mandrel in a solution of potassium bichromate prior to deposition. A flash (.0001") of hard chromium plating on the master can also act as a parting agent.

All of the above test results, coupled with Camin Laboratories past experiences with the machining of pure nickel, made nickel an ideal choice for a master plate material.

### C. Creation of Orifices.

The orifices in the injector plate can be formed by positioning a disposable pin into the master plate -- which then forms a hole when it is removed from the electroform. A second method would be to incorporate precise I.D. tubing into the master. The electroforming operation would then "lock" the orifices, formed by the tubes, into place. The investigation of means of creating orifices divided itself into two categories;

mechanical problems associated with obtaining pins or tubes of suitable accuracy and finish and
 electrochemical problems associated with deposition of metal around the pin or tube.

Although very precise I.D. nickel or stainless steel tubing could be obtained commercially
in the .010" to .030" diameter sizes required, electrochemical problems eliminated their use. Any pin
or tube which is electrically conductive and protrudes from the master plate will act as a high
current density point. As a result there is a heavier thickness of deposited metal at the tip of the
pin than at the pin-plate interface. As the metal
on the pin tip grows it acts as a shield, causing
voids in the region of the master plate.

Various types of non-conducting materials were evaluated as to their suitability for use as the orifice creating mechanism. The pin material must be resistant to attack by the electroforming bath, and permit removal from the electroform by thermal or chemical means which are compatible with the nickel electroform. Ideally, the material should be commercially available in rod form with precise diameters below .030".

Nylon, teflon, lucite, and bakelite with various filler materials were evaluated initially. Since none of these were available with the dimensional and surface finish tolerances required for injector orifice formation, an effort was made to machine the pins from oversize stock.

Concurrently, an electrochemical investigation was initiated using nominal 1/32" diameter stock positioned in master nickel plates, for the purpose of examining the problems of plating at the pin-plate interface. In all cases the deposit grew from the master plate outward, with dense deposited nickel at the pin-plate interface. No special shielding or high current density area problems were encountered. Tests were conducted with pins inserted at angles varying from zero to 65 degrees perpendicular to the plate.

Additional tests were conducted with groups of pins representing triplets and doublets. The center to center pin spacing varied from 1/16 inch to 1/8 inch. The purpose here was to examine the metallic deposition in the region between the pins and under the acute angle formed by the pins.

Solution agitation, coupled with gentle cathode (work piece) rocking resulted in dense deposits throughout the unit. There is of course a tendency for the metal to deposit at a faster rate on those portions of the master that do not contain protruding pins. However, since the initial layer of nickel required for an injector face is on the order of .100", the extra nickel that will accumulate in the open portions of the plate (perhaps .030"-.050") does not warrant developing current shields.

With the electrochemical problems apparently resolved, attention was directed to obtaining precise small diameter non-conductive rod or tube with a controlled exterior finish. While some materials such as lucite and linen-base Bakelite, can be readily machined into small diameter pins (.015" prox.), the surface of the pin contains tool marks which are reproduced on the interior surface of the orifice. Other materials, nylon and teflon, are difficult to machine to the required diameters due to their poor rigidity. These results turned our efforts towards obtaining extruded or drawn pins or tubes. A desire to utilize commercially available

products led to experimenting with aluminum and glass.

Aluminum is, of course, electrically conductive. An effort was made to render the surface of the aluminum non-conductive by anodizing. Preliminary samples of anodized aluminum rod contained porous coatings -- thus enabling the pin to act as a conductor with resultant excessive tip buildup. One advantage that would accrue from the use of aluminum is the ready removal of the pins from the electroform by immersion in hot caustic -- without attack on the nickel electroform. However, experiments using glass tube or rod were so successful, that the effort to develop the anodized aluminum concept was abandoned.

Glass has several distinct advantages as a material for creating orifices.

- 1. Availability in the sizes required from several outside sources.
  - Completely non-conductive.
  - 3. Accurate exterior dimensions.
  - 4. Rigidity.

5. Controlled surface finish -- mirror finish in the "as drawn" state or controlled roughness via etching.

Experimentation with glass indicated that all of the results obtained in the plating experiments with other non-conductors can be accomplished with glass. The problem then, was one of removal of the glass from the electroformed nickel and master plate. This can be accomplished by immersion in hot sodium hydroxide or hydrofluoric acid. As discussed in section B above, this has no deleterious effect on the nickel electroform or nickel master plate. In order to dissolve the glass as rapidly as possible, tubes rather than rods were used.

Glass tubes were obtained from a manufacturer of capillary tubing in nominal .020" and .030" outside diameter sizes. The smaller tube was found to be .0195  $\pm$  .0002, while the larger tube was .0305  $\pm$  .0001. The sample lot inspected represented a sufficient quantity of tubing to fabricate several hundred injectors, since each orifice will only require approximately a 3/8" length of glass. Examination of the glass samples under a microscope indicated no surface imperfection.

Samples of the glass were inserted in a nickel master plate, Figure 26, and a metallic deposit accumulated. The electroform was stripped from the mandrel and the glass was dissolved by immersion in hydrofluoric acid. The electroformed shell appears as shown in Figure 2a. The skirt on the shell results from allowing the nickel to deposit on the largest circumference of the mandrel as well as the face. The need for this is discussed in the next section. The electroform was sectioned to show the cross section of the orifice and again to examine the interior surface finish of the orifice. Since the pin was at an angle to the plate, the cross section of the orifice is elliptical, (Figure 3b). The purpose of this examination is to show the intimacy of the electrodeposited metal with the glass tube and the resulting smoothness or roundness of the hole. The interior walls of the orifice faithfully reproduced the mirror-like finish on the O.D. of the glass tube. As a result, the photo of the orifice surface, (Figure 3a) is poor due to the high reflectivity.

# IV. DESIGN AND FABRICATION OF PROTOTYPE INJECTORS

The purpose of this phase of the program is to utilize the developments of the laboratory study in the design and fabrication of doublet and triplet injectors. The major emphasis is to obtain several units of each configuration and demonstrate hardware reproducibility. The basic advantages of electroforming would be utilized in developing a unitized structure, i.e., a one piece injector. No particular design goals were established in terms of flow rate, orifice distribution, size, etc. Accordingly an 8 on 8 doublet and 12 on 6 triplet were selected. The orifice layouts for the master plate are shown in Figure 6 and 7. The master plate represents a transfer of the final injector plate. Drawings of the doublet and triplet injector are shown in Figures 8 and 9. The internal manifolding for both sets of orifices is at the same distance from the injector face. However, if a consideration of orifice length to diameter ratio, or any other reason, dictates that the manifolding should be at

different levels, this can be readily accommodated during the electroforming process. A detailed discussion of the fabrication procedure follows.

A nickel master or mandrel blank is fabricated in accordance with Figure 10. The 3/8-24 tapped hole is for a cathode rod that will support the unit in the bath. The holes to accept the glass tubing are drilled in accordance with Figures 6 or 7. A photo of the mandrel and glass tube is shown in Figure 2b. After machining the master is thoroughly cleaned and degreased as follows;

- 1. Pumice
- 2. Wash in methyl-ethyl-ketone
- 3. Hot alkaline clean in Enthone 808. The work piece is held anodic at 80 amperes/sq.ft for two minutes
  - 4. Rinse in water
  - 5. Immerse in 10% HCl
  - 6. Rinse in water

Three non-conducting plastic screws are threaded into the outer circumference of the mandrel. The screw heads are allowed to protrude above the mandrel, approximately 1/2 inch. The entire mandrel

body, with the exception of the face containing the orifice holes and the circumference containing the plastic screws is masked with a plastic tape. This is to prevent deposition of nickel in those areas that are masked. Deposition will then occur on the face of the mandrel and around the large circumference surface enclosing the threaded portion of the plastic screws. The 2-1/2 inch diameter section of the mandrel is to serve as a chucking piece for subsequent machining operations. The back surface of the mandrel is to serve as a reference surface for dimensional control. During the machining operations the three 1/4-20 plastic screws are replaced by steel screws, which prevent motion of the electroform with respect to the mandrel.

The glass tubes are inserted in the mandrel and the entire unit is cleaned in the Enthone 808 and rinsed in HCl. A five minute immersion in potassium bichromate serves to passivate the surface and prevent adhesion of the nickel deposit. The unit now enters the electroforming bath and begins to form an injector.

After sufficient metal has been deposited for the first machining operation, (in this case .120" minimum thickness) the unit is removed from the electroforming bath. The machining operation is performed in accordance with Figures 11 and 12. The surface of the deposit is turned to within .120" of the mandrel-injector interface. The circumferential and radial manifolding is end-milled according to print to a depth of .030. For both of the present injector designs, manifolding of both sets of orifices is accomplished at the same distance from the injector face. If a particular design requirement dictates manifolding at various distances from the injector face, then only that manifolding that is closest to the injector face would be machined at this time. During these machining operations the portions of the glass tubes that are creating orifices are of course broken. demonstrated during the laboratory scale program that the portions of the glass embedded in the nickel electroform remain intact and prevent the machining operations from peening over or distorting the orifice at the machined surface. At this point the embedded glass is removed by immersing the electroform and mandrel in a 25% solution of hydroflouric acid. The entire assembly is then cleaned by ultrasonic agitation in trichlorethylene.

The slave (injector) can now be removed from the master (mandrel). The mandrel is now available to start the next injector. The injector face or slave is fitted with a dummy master that has been machined in accordance with Figure 10, except that the glass positioning holes are not necessary. Three plastic 1/4-20 screws are used to attach the electroform to the mandrel. The entrances to the orifices are inspected, deburred and/or rounded as required. The manifold areas are filled with a wax filler material which is rendered conductive by applying a silver paste to the surface. If separate levels of manifolding had been required, those orifices which have not been manifolded would be refitted with glass tubes. This concept has been thoroughly tried and proven during the laboratory phase of the program.

After masking those areas of the mandrel that are not to receive deposited metal, the work piece is electrochemically activated and placed in the

electroforming bath. If a second layer of manifolding is required, the work is removed from the bath after sufficient nickel has been deposited to perform the manifold machining. For the prototype units fabricated on this project, this is not necessary and the work remains in the bath until a minimum of .250 inches has been deposited. units are then machined in accordance with Figures 8 and 9. Holes for the feed tubes are drilled into the manifold providing an outlet for the filler material which is melted and removed prior to welding the inlet tubes in place. The completed units are again placed in an oven at 300°F and flushed with methyl-ethyl-ketone to remove any residual filler material. Suggested variations for providing tube feed holes and attaching the tubes to the injector body are discussed in Section VII, Conclusions and Recommendations.

A photograph of a completed injector is shown in Figure 1. A sectioned triplet injector which shows the manifolding and orifice inlets is shown in Figure 5.

#### V. INJECTOR TEST PROGRAM

The prototype units (doublets and triplets) were submitted for water flow calibration for the purpose of defining hardware reproducibility. The tests were conducted by Ogden Technology Inc. (formerly United Aerotest Laboratories) of Deer Park, New York. A copy of their report is included as Appendix B.

During the calibration tests, no effort was made to obtain a back pressure on the injector other than atmospheric. Since the purpose of the tests was to examine reproducibility, any reduction in flow due to cavitation would have a similar effect on similar injectors. The pressure drop across the injector is therefore the pressure just upstream of the feed tubes.

The doublet injectors (units 5, 6, 7, 8) consist of 8 (.030 in.) orifices fed by four 1/8 inch diameter tubes manifolded internally, and 8 (.020 in.) orifices fed by a single 1/4 inch diameter tube.

The calibrations for the .030 inch orifices and .020 inch orifices are shown in Figures Bl and B2 respectively. In each case three out of the four units tested reproduced results within the range of the accuracy and readability of the instruments. The flow rate for the fourth unit was approximately 10% lower at the highest pressure drops. Note also that it is a different injector in each case. Among the possible causes are; burrs on the holes drilled for the feed tube, a constricted tube during the welding process, metal chips from the tube hole drilling process constricting an orifice, etc. This problem is discussed further in Section VII.

The triplet injectors (units 2, 3, 4) consist of 12 (.030 inch) orifices fed by a single 1/4 inch diameter tube and 6 (.020 inch) orifices fed by three 1/8 inch diameter tubes manifolded internally. The results of the calibration are shown in Figures B3 and B4. The .030 inch diameter sides are alike to each other within plus or minus 1.5%, while the deviation of the .020 inch diameter sides are within plus or minus 3%.

Unit number 1 (a triplet) was the first unit to complete the fabrication cycle. Accordingly, it was dissected prior to fabrication of units 2 through 8 in order to check adhesion, filler material removal, cleanliness, etc., (see Figure 5).

Visual inspection of the injector patterns was made during the calibration tests. Jet direction, jet characteristics and impingement was good for all units. Photographs of the spray patterns are shown in Figure 4.

# VI. ANALYSIS OF APOLLO SERVICE MODULE RCS INJECTOR

Module reaction control system rocket engine injector. The purpose of the analysis was to recommend methods by which the electroforming process could contribute to the design and fabrication of the S/M RCS injector. A study of the drawings for the mechanically fabricated unit, clearly indicates that an electroformed duplicate is not feasible. The basic cause prohibiting the manufacture of an electrodeposited duplicate is the total thickness of the injector. Except in unusual circumstances, electroforming should not be used to create structures in excess of 1/2 inch in thickness.

However, a similar injector, in the sense of orifice size and location could be electroformed. The internal manifolding would be rearranged so as to provide for a total thickness consistent with the electroforming process. The electroformed version would be an integral unit devoid of welds,

brazes, bolts, etc. A distinct possibility exists for regeneratively cooling the preignition chamber using the Camin integral cooling passage (Ref. 1, 2, 3).

#### VII. CONCLUSIONS AND RECOMMENDATIONS

The basic purpose of the present project is to define and develop the electroforming process variables and techniques required for electrodeposition of liquid propellant rocket motor injectors. It is submitted that demonstration of such feasibility will result in less expensive and more reliable injector systems. At the same time, internal manifolding and orifice distribution would not be limited by mechanical fabrication restrictions.

A laboratory scale program was conducted wherein a system of using glass tubes protruding from a nickel mandrel was developed for the fabrication of injectors. Electrodeposited nickel envelopes the glass tubes, thereby creating orifices when the glass is removed from the electroform. Internal manifolding of orifices is accomplished by machining the back of the electroform and inserting a disposable filler material into

the machined grooves. Subsequent nickel deposition, adherant to the initial electroformed nickel envelopes the filler material. Upon completion of the unit the filler material is removed either thermally or chemically, thus creating a hollow manifold system. Inspection and deburring of the orifice entrances is accomplished after the manifold machining step.

Feasibility of the process was demonstrated by fabricating a series of doublet and triplet injectors which were submitted for hydraulic testing for the purpose of defining hardware reproducibility.

It is recommended that the next logical step in the development of electroformed injectors be the fabrication of a unit similar to the S/M RCS injector. The design objectives should be restricted in the area of propellant flow rates and injection system operating conditions, but should be flexible in the areas of internal manifolding and orifice layout. At the same time an effort should be expended for process improvement. In particular, the method of drilling feed tube holes and subsequently

welding them in place should be eliminated. Drilling these holes can cause internal burrs or metal chips to be lodged in the internal manifolding. A suggested variation is to "grow" the hole by inserting a cylindrical core in the filler material that is creating the internal manifold. During deposition of the last thickness of nickel, the presence of the core will result in a feed tube hole when the core is removed. The possibility of electroforming the feed tubes to the injector body should also be investigated.

#### VIII. REFERENCES

- 1. Fialkoff, S., Mark, R., Webb, M. J., and Glassman, I. "Fabrication, Structural and Heat Transfer Considerations in Electroformed Rocket Nozzles," Progress in Astronautics and Rocketry, Vol. 2, Liquid Rockets and Propellants, Academic Press (1960), Pg. 563.
- 2. "Electroforming A New Technique for Fabrication of Rocket Motors." Camin Laboratories Final Report on Contract NOw62-0870-c Bureau of Naval Weapons, Department of the Navy.
- 3. Judge, John F., Missiles and Rockets, August 2, 1965.

### LIST OF FIGURES

- 1. Completed injectors
- 2a. Electroformed shell showing orifice and skirt
- b. Master mandrel with glass tubes in position
- 3a. Surface of orifice I.D.
- b. Cross section of electroformed orifice
- 4. Spray patterns from injectors
- 5. Sectioned injector showing internal manifolding
- 6. Orifice layout for doublet injector
- 7. Orifice layout for triplet injector
- 8. Doublet injector
- 9. Triplet injector
- 10. Mandrel
- 11. First Machining doublet injector
- 12. First Machining triplet injector

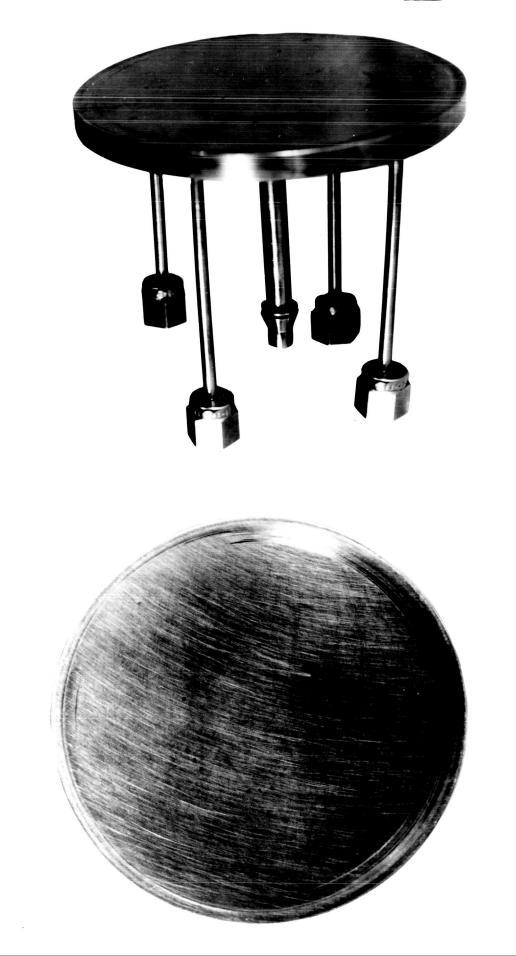
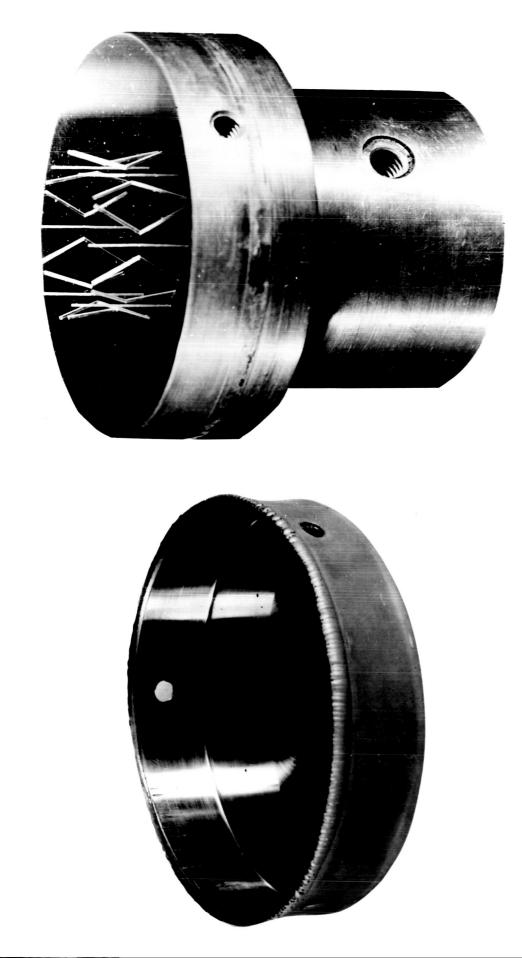


FIG. I: Front and side views of finished injectors.



Master mandrel with glass tubes in position. Electroformed shell showing holes and skirt. a to FIG. II:

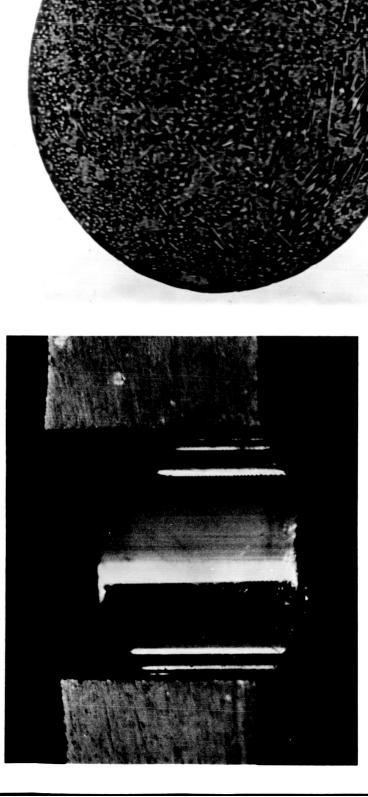




FIG.III: a. Highly reflective interior finish of orifice. b. Enlargement (500x) showing roundness of orifice.



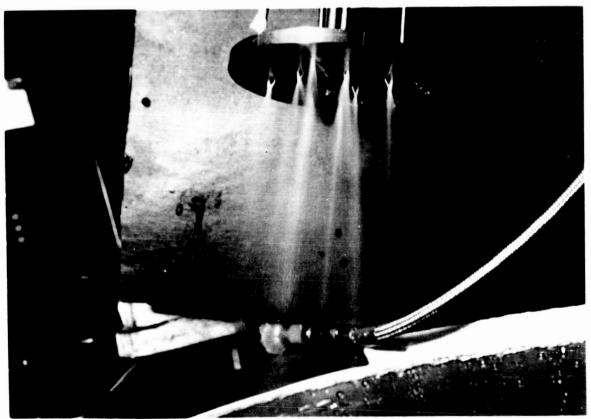


FIG. IV: Spray patterns of doublet and triplet.

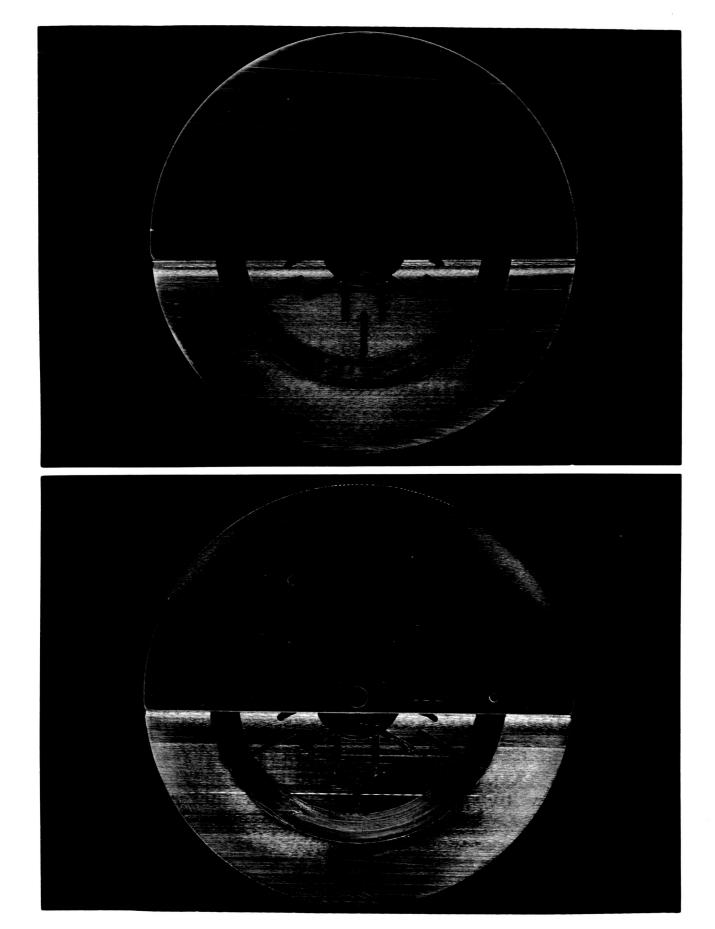


FIG. V: Sectioned injector showing manifolds and orifices on face and back.

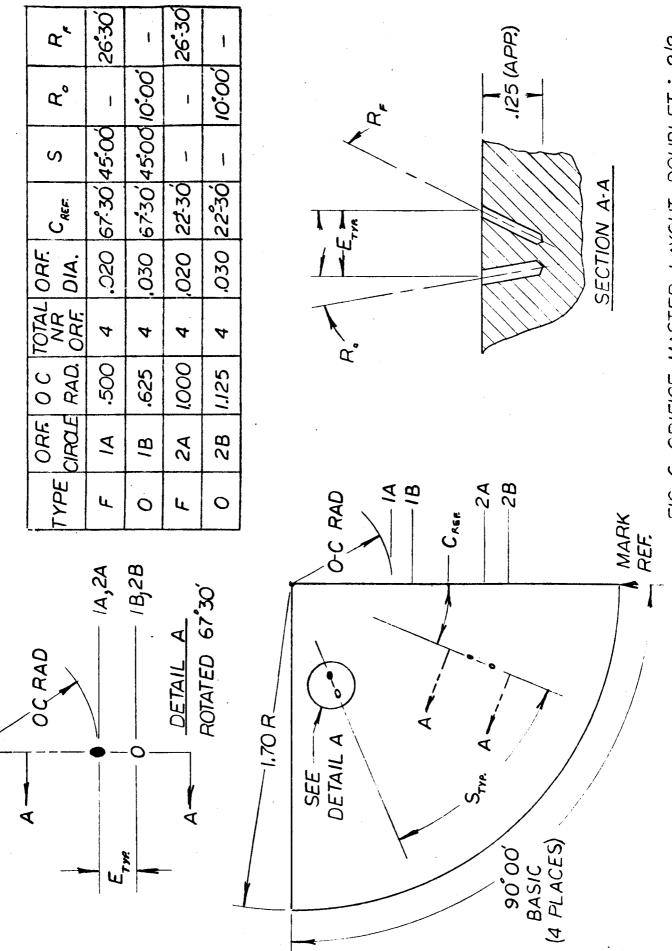


FIG 6 ORIFICE MASTER LAYCUT DOUBLET: 8/8

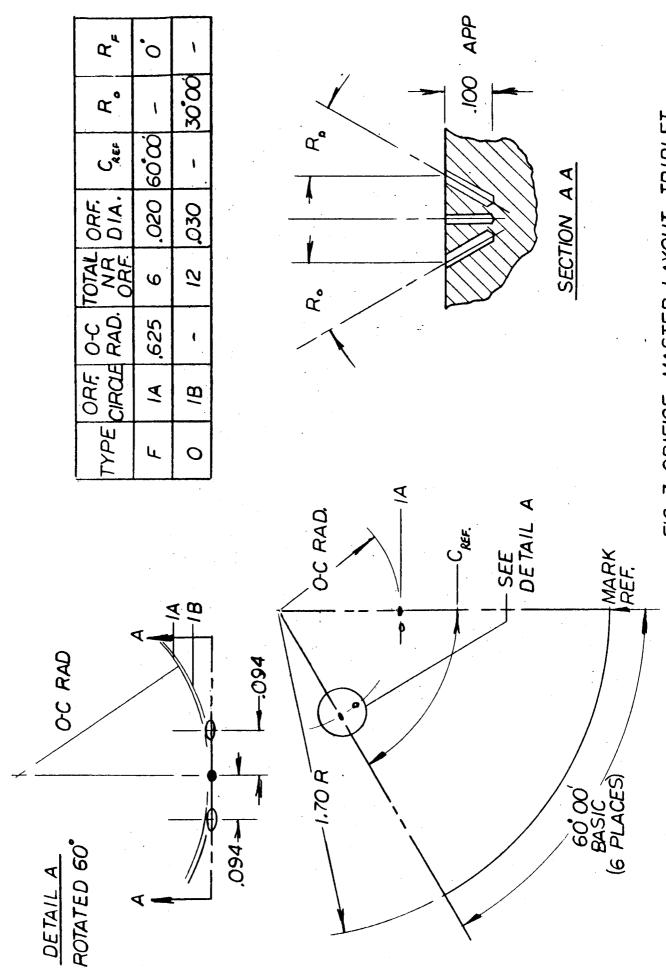
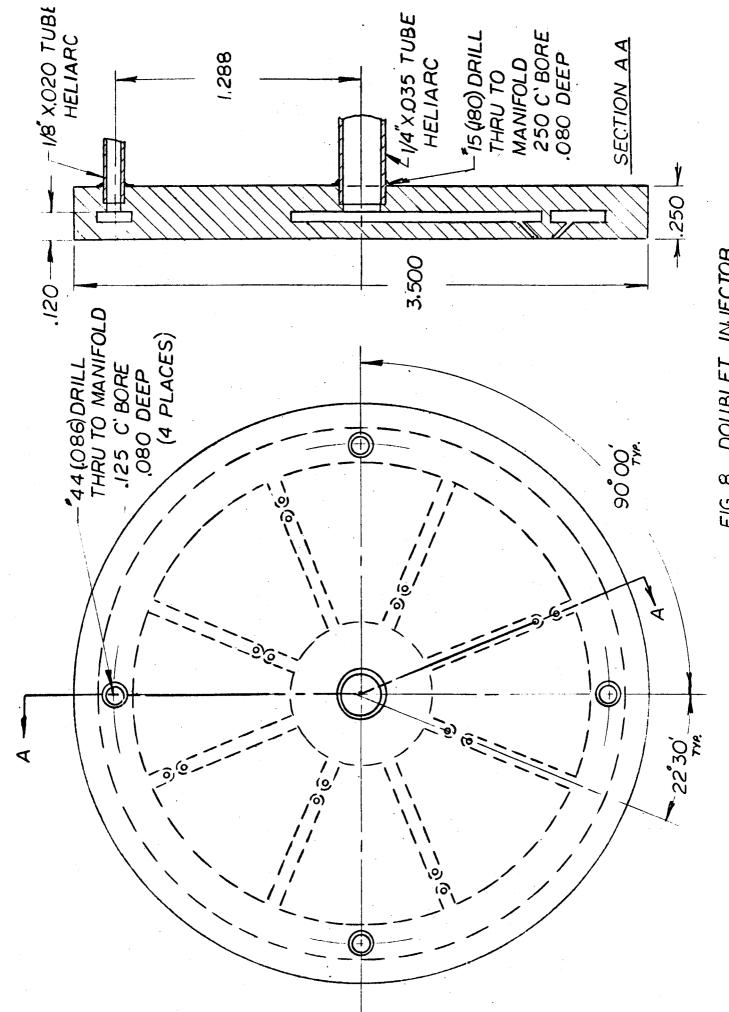


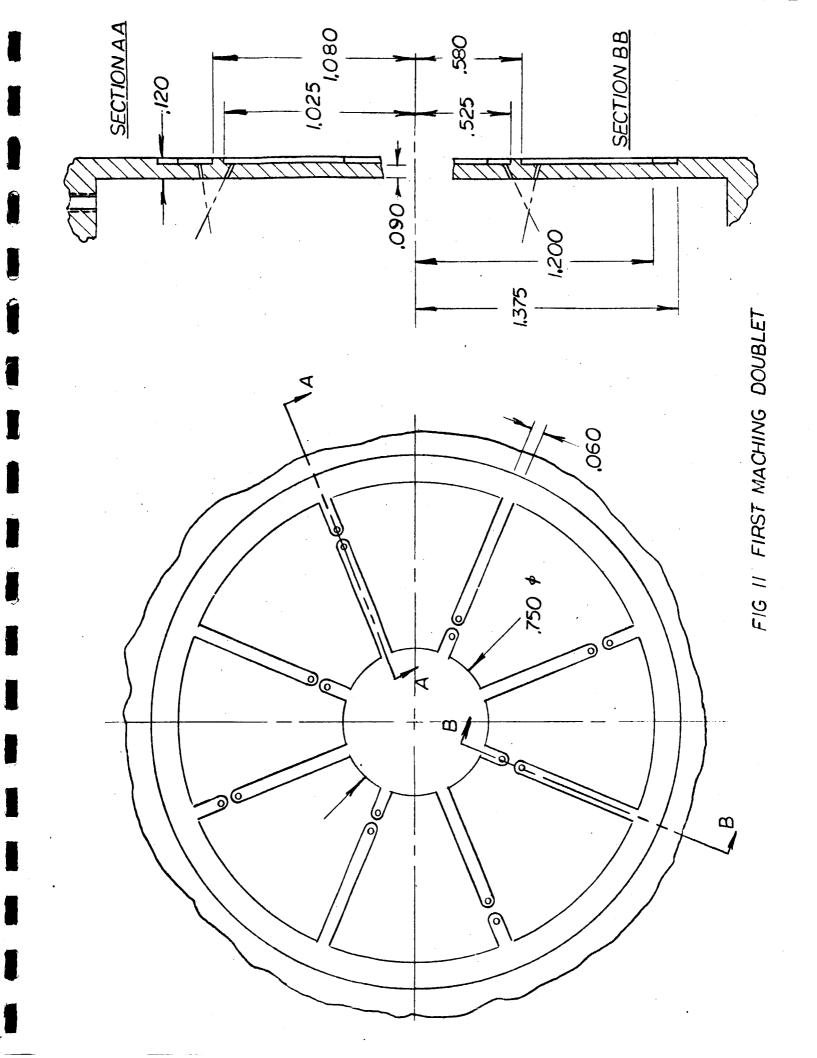
FIG 7 ORIFICE MASTER LAYOUT TRIPLET



DOUBLET INJECTOR F1G 8

FIG 10 MANDREL

MAT'L NICKEL 200



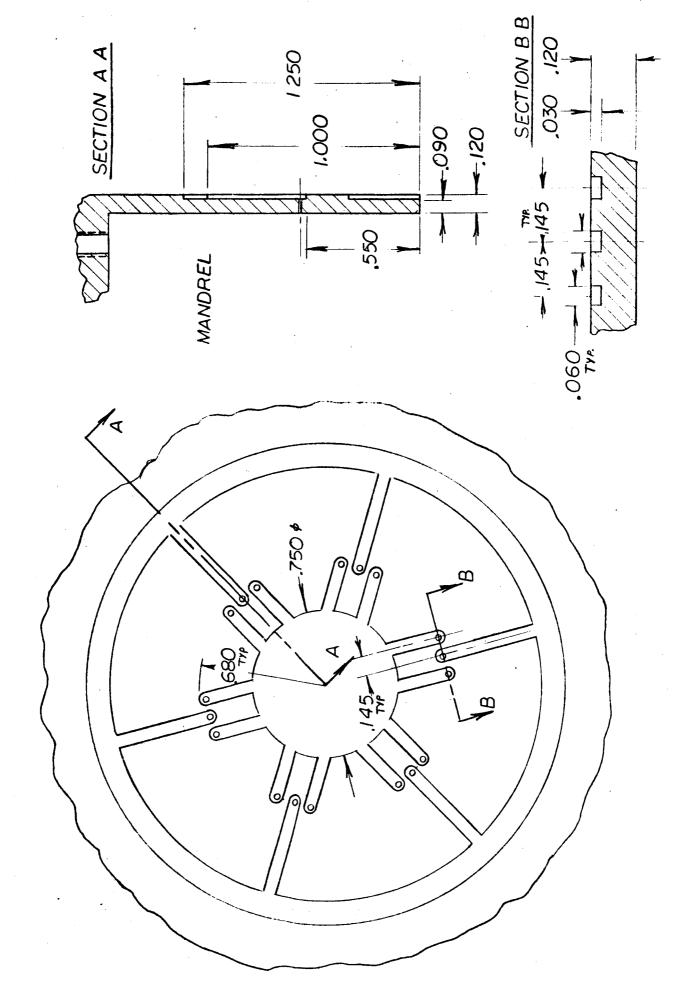


FIG 12 FIRST MACHING TRIPLET



# Lucius Pitkin, Inc.

RSTABLISHED 1865

#### METALLURGICAL CHEMISTS AND CONSULTANTS



Weighers - Samplers - Assayers - Analysts Mineralogists - Metallographers - Spectroscopists

Main Office and Laboratories

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# REPORT

September 7, 1966

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Camin Laboratories 104-14 So. 4th Street Brooklyn, New York

Attention: Dr. S. Hammer

Subject: TENSILE TEST OF NICKEL BARS

Three 1/4 inch O.D. by 1/8 inch I.D. nickel tensile bars were submitted to the Pitkin laboratories.

Tensile tests were performed at room temperature, 500 and 1000 F  $\pm$ 5F. The specimens tested at 500 and 1000 F were held for 15 minutes at the required temperature prior to testing.

Results of tests are shown on the appended table.

LUCIUS, PITKIN, INC.

A//J. Vecchio

AJV/mb/4





# Lucius Pitkin, Inc.

# METALLURGICAL CHEMISTS AND CONSULTANTS TESTING LABORATORIES

**47 FULTON STREET** 

PITKIN BUILDING

NEW YORK 38, N. Y.

To:

Camin Laboratories 104-14 So. 4th Street

Brocklyn, New York

Attn.: Dr. S. Hammer

Order No.

Lot No.

Vendor P.O.

Client P.O.

Report No. L.P. 650559

Project No.

Date September 7, 1966

Spec. No.

Part No.

Material: NICKEL TEST BARS

COMPOSITION									
Sample Number	Specified								
Compliance				=					
		PHYSICAL	PROPERTI	ES					
Sample Number O.D.,in. Size I.D.,in. Area,sq.in Yield Strength PSI	Specified	$ \begin{array}{r} 1\\ 0.\overline{250}\\ 0.125\\ 0.0364\\ 106,500 \end{array} $	2 0.248 0.125 0.0356 71,500	$ \begin{array}{r} 3 \\ 0.251 \\ 0.125 \\ 0.0367 \\ 27,600 \end{array} $					
Ultimate Strength PSI Elongation % 1 in. Reduction Area %		20.0	25.0	42.0					
Fracturgoad, lbs.		3,880	2,540	1,010	·				
Test Temp. ±5F	·	R.T.	500 F	1000 F					

Copies:

Subscribed and sworn to before me

this day of , 19

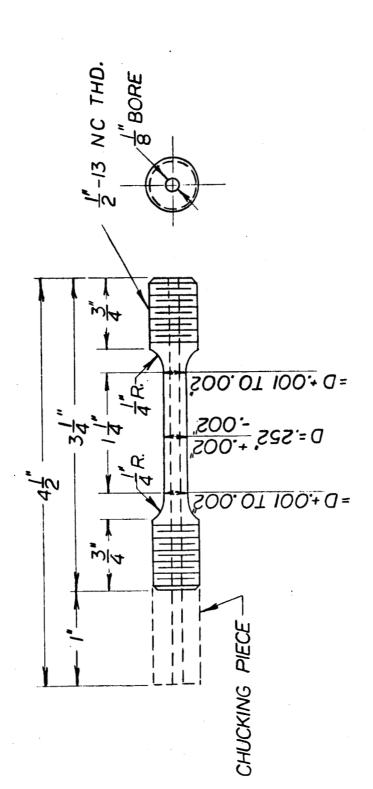
We hereby certify that the above is a true report of the results of analyses and tests as made by us on the samples indicated.

LUCIUS PITKIN, INC.

By:

FORM 74 3-58 2M

AJV/mb



CAMIN LABORATORIES TENSILE SPECIMEN FOR HOT TENSILE TEST



# OGDEN TECHNOLOGY LABORATORIES, INC. Subsidiary of OGDEN CORPORATION

REPORT OF

FLOW VERSUS DIFFERENTIAL PRESSURE TEST

ON

INJECTOR ASSEMBLIES

Performed by

Ogden Technology Laboratories, Inc. Deer Park, Long Dsland, New York

for

CAMIN LABORATORIES 104-14 SOUTH FOURTH STREET BROOKLYN, NEW YORK

MAY 1967

Test Report No. 6E67-3 OTL Job Number 7363





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APPENDIX A - Test Data and Flow Curves

APPENDIX B - Figures



#### ADMINISTRATIVE DATA

TEST REPORT:

6E67-5

TEST CONDUCTED:

Flow versus Differential Pressure

MANUFACTURER:

Camin Laboratories

104-14 South Fourth Street

Brooklyn, New York

MANUFACTURER'S TYPE OR MODEL NO .:

Injector Assemblies

DRAWING, SPECIFICATION OR EXHIBIT:

None

QUANTITY OF ITEMS TESTED:

Seven (7) units

(3) Triplet Injectors S/N's 2, 3 & 4

(4) Doublet Injectors S/N's 5 thru 8

SECURITY CLASSIFICATION OF ITEMS:

Unclassified

DATE TEST COMPLETED:

8 May 1967

TEST CONDUCTED BY:

Ogden Technology Laboratories, Inc.

DISPOSITION OF SPECIMENS:

Returned to Camin Laboratories,

DATE OF TEST REPORT:

15 May 1967

MANUFACTURER'S PURCHASE ORDER NO .:

67-13

ABSTRACT:

See Test Results, para. 4.0 and Test Data, Appendix A.

1.0 GENERAL INFORMATION

1.1 Ambient Conditions

All tests were conducted under laboratory ambient conditions as follows:

Temperature:

70°+ 10°F.

Relative Humidity:

95% R.H. Maximum

Barometric Pressure:

Local ambient

Fluid Temperature:

60° to 70°F.

1.2 Test Measurement Tolerances

Pressure Gages

+ 1% F.S. Accuracy

Flow Meters

+ ½% F.S. Accuracy

1.3 Test Fluid

The test fluid for all tests was water prefiltered

through two (2) 10 micron (nominal) filters in series.

#### 2.0 TEST EQUIPMENT

- 2.1 Pressure Regulators (2)
   Nageldinger
   Model: 304
   Range: 0-1000 PSIG outlet pressure
   Calibration: None required
- 2.2 Accumulator (Bladder type)
   Greer Hydraulics
   Model: 10 Gallon 3000 PSIG
   Calibration: None required
- 2.3 Filter Assemblies (3)
   Purolator Products
   Model: AN6235-4A (10 micron)
   Calibration: None required
- 2.4 Digital Counter
   Berkeley
   Model: 5545
   OTL # A-111
- 2.5 Decade Amplifier
  Ballantine Labs
  Model: 220C
  OTL #A189
  Calibration: Before each use
- 2.6 Flowmeter
  Potter Aeronautical
  Model: 3/16-3A
  Range: 0.2 to 1.0 GPM
  OTL #F10
  Calibration: Yearly
  6/8/66; 6/8/67

2.7 Flowmeter

2.7 Flowmeter
 Potter Aeronautical
 Model: 3/8-1
 OTL #F-14
 Calibration: Yearly; 6/6/66,6/6/67

All instrumentation and equipment calibration is conducted in accordance with Specification MIL-Q-9858A as further defined in MIL-C-45662A "Calibration System Requirements" and is traceable to the National Bureau of Standards.

#### 3.0 TEST PROCEDURE

## 3.1 Test Article Description

The articles tested consisted of seven (7) samples of Injector Assemblies of two different types. Serial Numbers 2, 3 and 4 were termed "Triplet Injector Assemblies" and serial numbers 5 through 8 were termed "Doublet Injector Assemblies".

### 3.1.1 Triplet Injector Assemblies

The Triplet Injector Assemblies contained four inlet tubes; one center feed tube & inch in diameter and three outer peripheral tubes each 1/8 inch in diameter. The center feed tuke is manifolded by internal passages to twelve (12) 0.030 inch diameter orifices. The three (3) 1/8 inch diameter outer feed tubes are manifolded commonly to six (6) 0.020 inch diameter orifices.

# 3.1.2 <u>Doublet Injector Assemblies</u>

The Doublet Injector Assemblies contained five inlet tubes; one center feed tube 1/2 inch in diameter and four outer peripheral tubes each 1/8 inch in diameter.

The center feed tube is manifolded by internal passages to eight (8) 0.020 inch diameter orifices. The four (4) 1/8 inch diameter outer feed tubes are manifolded commonly to eight (8) 0.030 inch diameter orifices.

### 3.2 <u>Test Requirements</u>

The test object was to calibrate each of the seven test articles with water under identical test conditions and establish the similarity of flow versus pressure differential characteristics of the injector assemblies. To establish similarity the test data was plotted on four sets of curves, one each for the following flow conditions:

- 1) Triplet injectors outer feed flow vs. pressure differential
- 2) Triplet injectors center feed flow vs. pressure differential
- 3) Doublet injectors outer feed flow vs. pressure differential
- 4) Doublet injectors center feed flow vs. pressure differential

#### 3.3 Calibration Procedure

The injector assemblies were installed individually in the test setup shown in Figure 1 of Appendix B. First the outer feed flow versus pressure differential was calibrated. Calibration was performed by adjusting the gaseous nitrogen pressure on the bladder accumulator to approximately 300 PSIG. The flow control valve was then adjusted to give the required inlet pressure at the injector assembly. Nitrogen pressurization was used in lieu of a pumping system to eliminate the pressure pulsations inherent in pumping systems. Pressure differential was read from the inlet pressure gauge since the nozzles were exhausting directly into atmospheric pressure. Flow readings for each assembly were taken at four different inlet pressure readings 50, 100, 150 and 200 PSIG for both increasing and decreasing flow. All readings were taken only after flow and pressure had completely stabilized.

#### 4.0 TEST RESULTS

The results of the flow versus pressure drop calibrations for the injector assemblies are presented in Appendix B=1. The data is presented and the curves plotted for four different conditions:

- 1) Triplet Injector Assemblies Outer feed flow versus pressure differential
- 2) Triplet Injector Assemblies Center feed flow versus pressure differential
- 3) Doublet Injector Assemblies Outer feed flow versus pressure differential
- 4) Doublet Injector Assemblies Center feed flow versus pressure differential

The data presented was taken during stabilized flow and pressure conditions under both increasing and decreasing flow calibrations.

#### 5.0 RECOMMENDATIONS

None. Data merely submitted.

#### 6.0 SIGNATURES

OGDEN TECHNOLOGY LABORATORIES, INC.

muchael & Esposito

Prepared by: M.J. Esposito, Manager Mechanical Dept.

Reviewed by: R. Zeibig, Director Quality Assurance

APPENDIX B-1

Test Data and

Flow Curves

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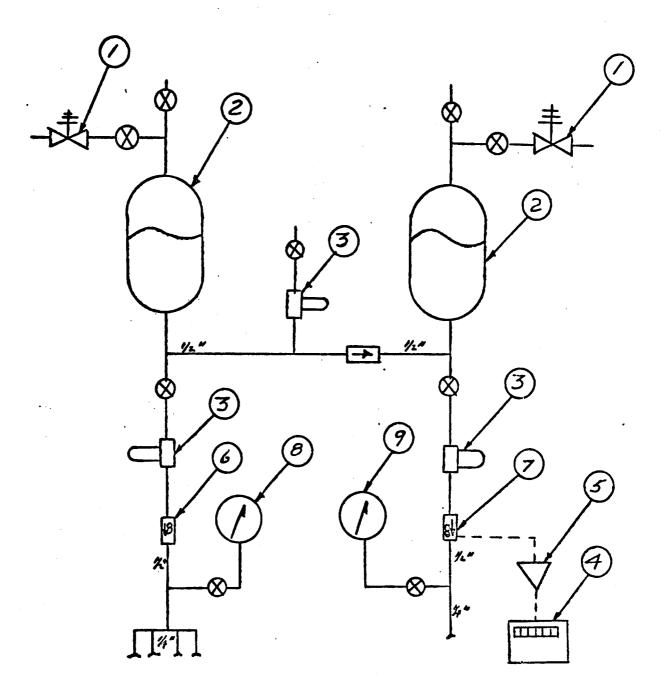
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NOTE: 1) All lines 1/4 inch unless otherwise specified

2) Item designations refer to section 2.0
For example 3 refers to item 2.3 filter assembly.

FIGURE 1 Flow vs. AP Test Schematic